

The Hungaria Asteroids: resonances, close encounters and impacts with terrestrial planets.

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Abstract The Hungaria asteroid family, which consists of more than 8000 members with semi-major axes between 1.78 and 2.03 AU, is regarded as one source for Near-Earth Asteroids. Named after (434) Hungaria these asteroids are relatively small (mean diameter ~ 1 km) and have inclinations of the order of 20° . They are mainly perturbed by Jupiter and Mars, and are ejected because of mean motion and secular resonances with these planets and then become Mars-crossers; later they may even cross the orbits of Earth and Venus. We are interested to analyse the close encounters and possible impacts with these planets. For 200 selected objects which are on the edge of the group we integrated their orbits over 100 million years in a simplified model of the planetary system (Mars to Saturn) subject to only gravitational forces. We picked out a sample of 11 objects (each with 50 clones) with large variations in semi-major axis and restarted the numerical integration in the model Venus to Saturn. Due to close encounters in connection with mean motion and secular resonances some of them achieve high inclinations and eccentricities which then leads to relatively high velocity impacts on Venus, Earth, and Mars. We report all close encounters and impacts with the terrestrial planets and statistically determine collision velocities of these fictitious Hungarias. With this data we compute the effect of the possible impacts with the terrestrial planets and estimate the diameter of the crater depending on the impact energy released, the impact velocity and the impact angle.

Keywords Hungaria group · close encounters · terrestrial planets · NEAs · encounter velocities

1 Introduction

There is evidence from meteorites that members of the Hungaria group may reach the terrestrial planets and be a source of impactors. In the first place this is deduced from spectra for the major component of the family, the E-type¹, which are consistent with the composition of some meteorites (aubrites, Zellner et al. (1977)) found on the Earth.

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¹ The majority of Hungarias is of E-type or Achondritic Enstatite (about 60%), followed by S-type (17.2%) and less C-types (6.0%) (Warner et al. 2009).

The objects of the group are not very big in size compared to the other Main Belt Asteroids (MBAs), they have an average diameter of $\sim 1 \text{ km}$ ² ranging up to 11.4 km, (434) Hungaria being the biggest member³. They have an absolute magnitude distribution that is quite homogeneous with a V-shape distribution in absolute magnitude versus semi-major axis, in an interval from ~ 11.5 to 18.5 mag (see Warner et al. (2009), in fig. 1). The reason for that might be that the majority of them have diameters around 1 km or slightly more, and an homogeneous albedo with little scattering (McEachern et al. 2010). The Hungarias have an average albedo of $p_v \sim 0.4$ (Warner et al. (2009), hereafter abbreviated as WH), which distinguishes them from other asteroids in the main belt having $p_v \sim 0.18$ or lower.

These bodies are located mainly inside a region which ranges from ~ 1.8 to ~ 2.0 AU (see section 2 for details); they are mainly influenced by the v_6 secular resonance (SR) and by the mean motion resonances (MMRs) 4:1 with Jupiter (J4:1) and 3:4 with Mars (M3:4). The majority of Hungarias have a retrograde rotation and similar spin rates (Pravec et al. 2008; Rossi et al. 2009). Warner and Harris (2007) found a consistent group of binaries (more than 10%) with fast rotating primaries, this presence being a sign of a collisional origin (Durda et al. 2004; Zappalá et al. 2002). Based on the study of Lemaître & Morbidelli (1994) on proper elements WH assumed that the Hungarias formed after a catastrophic collision of (434) Hungaria, presumably the largest fragment of the Hungaria collisional family. Starting from this collisionary assumption they computed an age for the family of about 0.5 Gyr, that comes from the degree of spreading versus size of family members. WH, considering 2859 objects (inside the curved lines of the V-shape mentioned previously) in the range $15.5 < H < 17$ mag and assuming a geometric albedo value of 0.38 (the same value as for (434) Hungaria), found a collective diameter of 26 km, thus the putative diameter of the former parent body.

Milani et al. (2010) confirmed this collisional origin, underlining the possibility of the presence of a subfamily, especially for the uniform number distribution in semi-major axis for values above 1.92 AU. They suggested a half life of 960 Myr and a diameter of 30 km for the parent body, in quite good agreement with WH. Bottke et al. (2011), in contrast to the previous suggestions about the origin, assumed that the Hungarias evolved from the depletion of a part of the primordial main belt with semi-major axes between 1.7 AU and 2.1 AU, i.e. they do not assume a collisionary origin.

2 Methods

The orbital elements of the Hungaria asteroids were taken from the data base of the Minor Planet Center (MPC)([HOME PAGE](http://www.minorplanet.org)). We extended our sample from the Hungaria family to a group⁴ covering the range $1.78 < a[\text{AU}] < 2.03$, $12^\circ < i < 31^\circ$ and $e < 0.19$ in orbital element space, following in part a suggestion of Spratt (1990), so that our sample finally consisted of 8258 asteroids (August 2010). Out of these we selected 200 according to a cri-

² computed from the average of the absolute magnitude, albedo, using the equation of Fowler & Chillemi (1992), see section 2 and table 1 too.

³ see database at <http://www.minorplanet.info/PHP/lcdbsummaryquery.php>

⁴ A “group” of asteroids is defined by a range of osculating elements (see also WH)—differently from the definition for a family of asteroids, that uses the proper elements. Families are defined by a specific clustering method, which gives dynamically a homogeneous sample of asteroid in the Main Belt, the most well known are the Hierarchical Clustering Method (HCM, Zappalá et al. (1990)) and the Wavelet Analysis Method (WAM, Bendjoya et al. (1991)).

terion based on the action variables⁵. Our study of the dynamics with respect to the transport to the terrestrial planets and the possible impacts was undertaken in different steps:

1. For our purpose of investigating statistically the close encounters with the terrestrial planets, we perform a study with only gravitational interactions and for this the Lie integration method (Hanslmeier & Dvorak 1984), with a specially designed program, is a very suitable one (Eggl et al. (2010) compared to other methods. We integrate the orbits of these asteroids in a simplified dynamical model for the solar system (Sun, Mars, Jupiter, Saturn + the massless asteroids)⁶ for 100 million years (Myr) to identify possible escapers, based on the variation in of the semimajor-axis. The escapers showed deviations from the group's mean semi-major axis of more than $\sim 7\%$ ⁷ of the total width of the group.
2. The 11 fugitives found (see table 1) were then dynamically investigated using additional 49 clones for every of the asteroids with slightly different initial conditions. We used a Monte-Carlo code generating random values for (a, e, i) , starting with the initial conditions of the real escapers in appropriate ranges: $a \pm 0.005$ AU, $e \pm 0.003$ and $i \pm 0.005^\circ$. The model for the solar system was now Venus to Saturn and the integration time was again 100 Myr.
3. During this integration we also reported the close encounters to the terrestrial planets inside the average lunar distance ($\lesssim 0.0025$ AU)⁸ from the planets' surface.
4. For the Hungarias we get physical parameters like their velocities, their angle of deflection⁹, and their resonances with the planets. At the end we have a statistics of close-encounters and impacts with the terrestrial planets. From the data we find some interesting results concerning correlations between physical parameters as the angle of deflection of a close encounter versus the minimal distance, or the orbital-inclination versus the angle of deflection again.
5. Finally we study the consequences of such an impact on the surface of the terrestrial planets and estimate the diameter of crater from the data derived before.

⁵ We chose a pseudo-metric like variable, namely: $d = \left| \sqrt{\left(\frac{e}{\langle e \rangle}\right)^2 + \left(\frac{a}{\langle a \rangle}\right)^2 + \left(\frac{\sin i}{\langle \sin i \rangle}\right)^2} \right|$

⁶ We have asserted that this model is enough analysing the orbit of three Hungarias of which two initially are very next to a resonance, 2000 *CJ33* next to *E2* : 5, *Tweedeledum* next to *V1* : 4 and 1999 *RE27* next to no important resonance and we found only one relative important deflection out of each own 100 clones.

⁷ We consider a Hungaria as an escaper (we will also call those who escapes "the fugitives" from now on) if it has a $\Delta a > \Delta a_{group}/16 = 0.015625$ AU, with $\Delta a = a_{max} - a_{min}$.

⁸ In order to be able to compare the values, in case of Mars and Venus we used a distance proportional to their Hill spheres scaled to the one for the Earth, so respectively 0.00166 AU and 0.00170 AU.

⁹ The angle between the asteroid's entering direction at 0.0025 AU and its exiting direction:

$$\cos \Theta = \frac{\mathbf{v}_{ent} \cdot \mathbf{v}_{exit}}{\|\mathbf{v}_{ent}\| \cdot \|\mathbf{v}_{exit}\|}$$

Asteroid	a [AU]	e	i [deg]	H_V [mag]	Diameter [km]
2002 RN137	1.8538	0.1189	22.82	16.9	1.01
2000 WN 124	1.9073	0.1062	17.11	16.2	1.24
1992 QA	1.8697	0.1116	26.23	15.3	1.88
Davasobel	1.9034	0.1178	27.81	14.7	2.48
2000 CR58	1.9328	0.1051	17.1908	16.5	1.08
1997 UL20	1.9894	0.1841	28.88	15.8	1.49
2001 XB48	1.9975	0.1055	12.32	16.2	1.24
1996 VG9	1.8765	0.1556	22.71	15.3	1.88
2000 SV2	1.8534	0.1843	24.97	14.9	2.26
1991 JM	1.8512	0.1263	24.50	16.8	0.94
1999 UF5	1.9065	0.1874	19.24	16.9	0.99

Table 1 Osculating elements for the escaping Hungarias: semi-major axis (a), eccentricity (e), inclination (i) in sexagesimal degree Absolute visual magnitude H_V , and diameter; data taken from the database “astorb.dat” of the Minor Body Center. We consider an average visual albedo of 0.38 ((Warner et al. 2009)), apart from 2002 RN137, which has a confirmed albedo of 0.3. These 11 asteroids also belong to the Hungaria family (see astdys website, <http://hamilton.dm.unipi.it/astdys/>, for comparisons with the elements), so we can speak about fugitives from the Hungaria *family* and 2 (Davasobel and 2002 RN137) of them fits with the ones in strongly chaotic orbit in Milani et al. (2010).

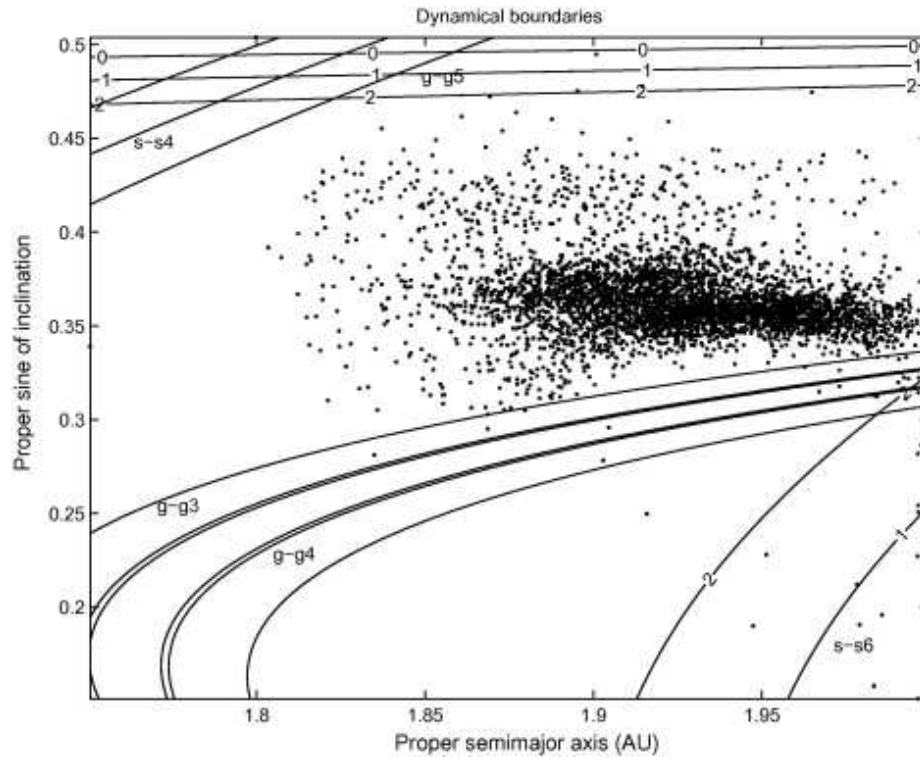


Fig. 1 Location of the Hungaria family of asteroids in a plot proper inclination (y-axis) versus the proper semimajor axis. The different secular resonances are explained in the text. (Picture taken from Milani et al. (2010). Courtesy permission from Prof. A. Milani and Prof. Z. Knežević)

3 RESULTS

3.1 Dynamical evolution and resonances

The Hungaria region is surrounded by four main linear secular resonances (Gladman (1997)): $g - g_5$, $g - g_4$, $s - s_6$ and $s - s_4$ (see Fig.1) which control the outer boundary. They pump up the inclination especially in the region between Mars and Earth up to 30° . In addition the 2:3 MMR with Mars and the 4:1 with Jupiter is acting there, but also and also some higher order secular resonances involving Jupiter and Saturn. Two of these resonances that turn out to be of great importance in the martian region are the $2g - g_5 - g_6$ and the $g - s - g_5 + s_6$. They act in the the martian region at low-orbital inclination (Morbidelli & Henrard (1991)), producing eccentricities that increase on time scales of a few hundred thousand years; in fact in our samples the fugitives show this dynamical behaviour. As one can see during the dynamical evolution the asteroids cross many mean motion resonances (MMRs) which perturb significantly the orbits.

These resonances act on the inclination of a clone of the asteroid 2002 RN137 around 50 Myrs (Fig. 2). Furthermore 2002 RN137 (fig. 2) is a good example for a NEA which changes from one NEA-family to another, starting to be an Amor at 64.015 Myr and then an Apollo for the first time at 72.669 Myr. The most important resonances are the J5:1 (that is

	close encounters to ...			close encounters only to ...		
	Mars	Earth	Venus	Mars	Earth	Venus
number	427	158	132	243	0	0
percentage	77.6	28.7	24.0	44.2	0.0	0.0

Table 2 Close encounters for the sample of 550 Hungarias during 100 Myrs with the terrestrial planets. Columnn 2 to 4 for every planet separately, Columns 5 to 7 for a planet alone

	close encounters to pair ...				close encounters only to pair ...		
	M & E	M & V	E & V	M & E & V	M & E	M & V	E & V
number	143	122	119	138	24	3	1
percentage	26.0	22.2	21.6	25.1	4.4	0.6	0.2

Table 3 Close encounters for the sample of 550 Hungarias during 100 Myrs with the terrestrial planets. Columnn 2 to 4 for at least two planets and columns 5 to 7 ONLY for two planets. M stands for Mars, E for the Earth and V for Venus

very important just before the object becomes a NEA), M7:9 and E5:12. Then there are the MMRs of higher order, E12:29, E8:19, E13:25, V7:17, V6:23, V8:31, V9:35, M16:63, and V11:43 and some 3BMMRs, that play a role when no MMRs is active (see fig. 3). There is the very high order 19:46 MMR with Earth which acts at high semi-major axes. The MMR where the asteroids stay for about 0.8 Myr are in particular: V9:35, M7:9. Just before it becomes a NEA and after having 2 close encounters with Mars (see fig. 2), V23:6 it is in for about 1 Myr at ~ 1.795 AU.

3.2 Close encounters

The sample of Hungarias which we used has a high probability ($> 77\%$) to have close encounters (CE) with terrestrial planets (especially with Mars) in the 100 Myr time interval. We show the detailed results in the respective Tab. 2 counting the CE for every planet separately (first three columns) and the CEs (last three columns) exclusively only to one of the terrestrial planets. By far most of the fictitious asteroids have such CE with Mars, which is not surprising because the Hungaria region is close to the orbit of Mars. Also the CEs to Earth and Venus is in the expected order, because the dynamical transport the the inner system needs more time for Venus than for the Earth and Mars. It also shows that almost half of the bodies just meet Mars and then they suffer either from being ejected far out or hit the Sun (see later). None of them have only CE with the Earth and only one CE exclusively with Venus. In Tab. 3 (first three columns) the encounter probabilities for two of the planets is not different for any pair and also not for CE with all three planets. That an object meets only a specific pair is very low especially for Mars an Venus and Earth and Venus.

In Tab. 4 one can see that the average time for a first close encounter with Venus is quite long (~ 63 Myrs), but it quite surprises that this time is not much smaller for the Earth (~ 63 Myrs). For the first CE with Mars the average time is very low (~ 14 Myrs); we already explained it with the relatively closeness of the semimajor axes of Mars with the perihelion distances of the Hungarias.

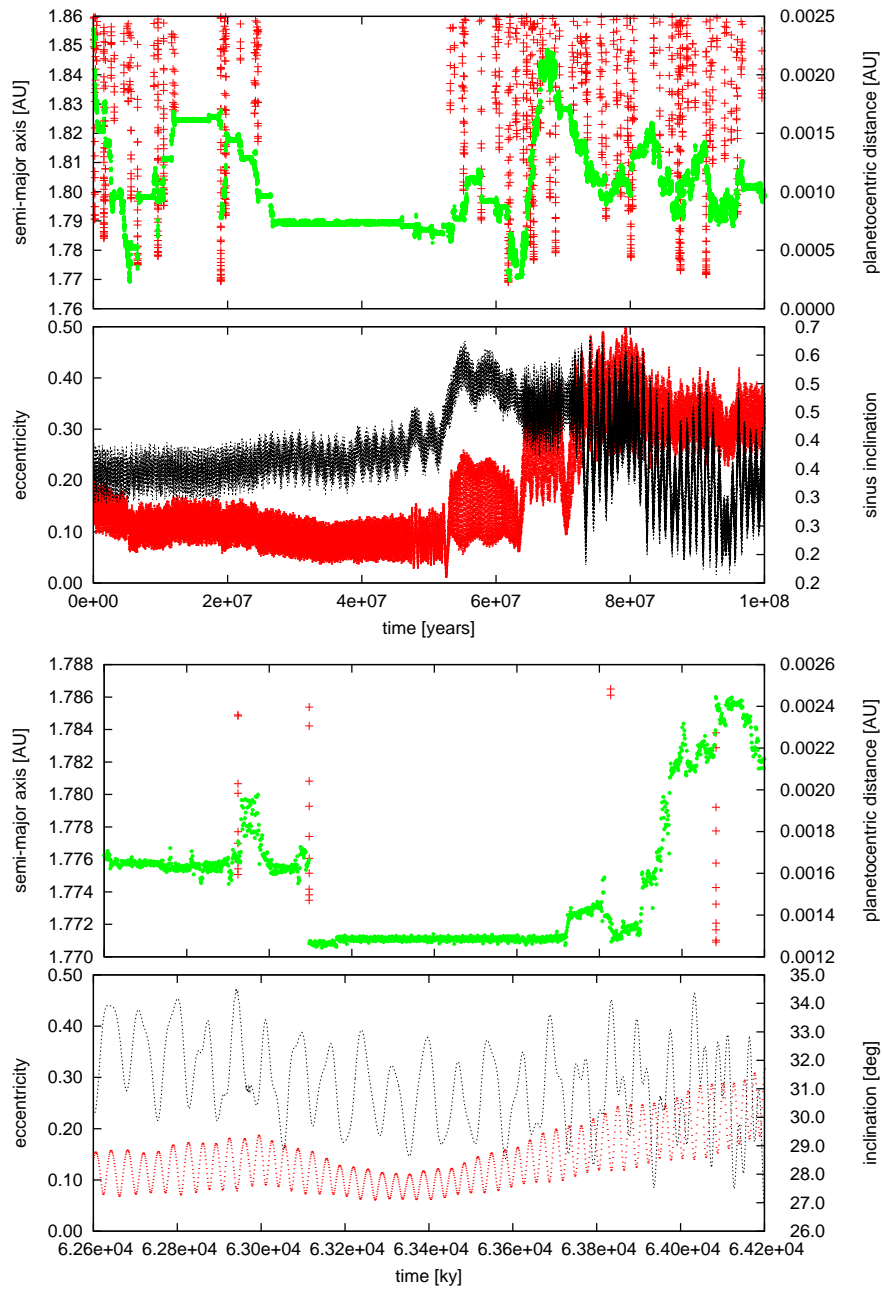


Fig. 2 Dynamical evolution of a clone of 2002 RN137 over 100 Myrs. From top to bottom: Semimajor axes (left, green) and planetocentric distances in AU of approaches to Mars (right, red crosses); Eccentricity (left, black) and inclination ($\sin(i)$, right, black). Clearly in the upper graph for a certain period of time the object has no close encounters with Mars. Lower: Zoom of upper picture inside the interval of time just before the asteroid becomes an Amor. There is a very well defined periodicity of the eccentricity, with a feeble average increase due to the two resonances V23:6 and J146:29. A periodicity is visible also in the inclination, which is decreasing slowly.

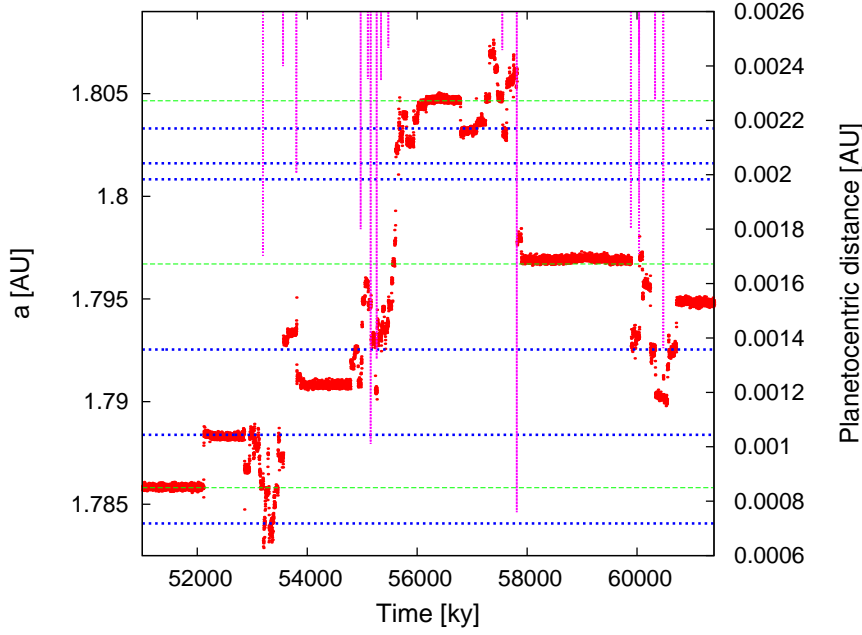


Fig. 3 Dynamical evolution for a clone of 2000 RN137 around 5Myrs which becomes an Amor and then an Apollo: semimajor axes (left, red) and minimum distance to Mars. NEA. Resonances are indicated with straight horizontal lines (for more see text) also indicated are the resonant values in semi-major axis. Vertical lines shows when close encounters with Mars happen. The resonances act at (MMRs in dots and 3BMMRs in dashes): 1.803304 AU for M16:63, 1.8030388 for E19:46, 1.80161075 for M7:9, 1.80083 for E12:29, 1.79457 for V11:43, 1.792536 for E5:12, 1.7883847 for V9:35, 1.784064 for V8:31; 1.7858034 for J7:S-5:-1, 1.796702 for J20:S-13:-3 1.804655 for J13:S-8:-2. Red color is for the evolution of the semi-major axis for the clone (of 2000 RN137) semi-major axis.

In Tab. 5 the average time $\langle T_{pl} \rangle$ for an object to become member of a NEA family is listed, where one sees again the increasing number of this time $\langle T_{pl} \rangle$ from the outer NEAs (the Amors) to the inner ones (the Atiras). In short this four groups are characterized by their orbital elements a follows

- **Atiras** NEAs whose orbits are contained entirely with the orbit of the Earth (named after asteroid 163693 Atira) with $a < 1.0$ AU, $Q < 0.983$ ¹⁰ AU
- **Atens** Earth-crossing NEAs with semi-major axes smaller than Earth's (named after asteroid 2062 Aten) with $a < 1.0$ AU, $Q > 0.983$ AU
- **Apollos** Earth-crossing NEAs with semi-major axes larger than Earth's (named after asteroid 1862 Apollo) with $a > 1.0$ AU, $q < 1.017$ AU
- **Amors** Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars' (named after asteroid 1221 Amor) with $a > 1.0$ AU, $1.017 < q < 1.3$ AU

We argued that not all objects have close encounters to the planets, some will be ejected into the outer belt region, some may become Sun-grazers and even falling into the Sun; a small number finish their lives colliding with the Sun (confirming Dvorak & Pilat-Lohinger

¹⁰ Note that $Q = a(1+e)$ is the aphelion distance of an object and $q = (1-e)$ its perihelion distance

Planet	$\langle T_{pl} \rangle$ [Myr]	$T_{pl,min}$ [Myr]
Venus	63.34	(2000 SV2) 10.9
Earth	62.45	(1997 UL20) 10.5
Mars	13.51	(1996 VG9) 0.07

Table 4 Average value of the time of CE with the planets for all objects (2nd column) and for the shortest time of a first CE with the planets for a single object 3rd column

Family	$\langle T \rangle$ [Myr]	T_{min} [Myr]
Amor	46.67	(2000 SV2) 0.09
Apollo	60.82	(1997 UL20) 1.68
Aten	61.44	(1997 UL20) 8.40
Atira	69.37	(1997 UL20) 8.92

Table 5 T = average time (of the real asteroid and the clones) when the object becomes member of the NEA family, T_{min} is the minimum time for the indicated object

Asteroid	Imp. Sun %/100Myr	$\langle P \rangle$ [AU/100Myr]	P_{min} [AU]
2002 RN137	2	0.90 ± 0.33	0.0000
2000 WN 124	0	1.55 ± 0.07	1.03
1992 QA	12	0.96 ± 0.30	0.0000
Davasobel	6	0.69 ± 0.19	0.0000
2000 CR58	2	1.61 ± 0.17	0.0000
1997 UL 20	16	0.82 ± 0.34	0.0000
2001 XB48*	15	0.54 ± 0.23	0.0000
1996 VG9	0	1.37 ± 0.07	0.16
2000 SV2	22	0.68 ± 0.37	0.0000
1991 JM	6	1.20 ± 0.20	0.0000
1999 UF5	4	1.07 ± 0.28	0.0000

Table 6 Number of clones per 100 Myrs per asteroid that end up as sun-grazers with the average perihelion and the minimum perihelion of one of their clones.

(1999)). A relative small number even have impacts with a planet; we will deal with the consequences in the next chapters. In Tab. 4 we show the percentage of our sample which finish their life as colliding with the Sun for every of the 11 fugitives. In particular clones of 2000 SV2 have the highest probability than the other to hit the Sun, and also 1997 UL20, 2001 XB48 and 1992 QA have high chances to do so, see table 4.

According to our statistics we can say that about 8 % from the escaping Hungarias end as Sun colliders within 100 Myrs. But this does not mean that this percentage of the whole Hungaria group will end like this: we picked out the ones with a high probability of leaving their group membership. From the first sample (200 fictitious asteroids out of ~ 8000) we found only 5% of escapers and from this ones only $<10\%$ of Sun-colliders. So our estimate of an upper limit of Sun-grazing Hungarias in the time scale of 100 Myrs is $<1\%$.

As example of an asteroid becoming a sun-grazer we show the dynamical evolution 2000 SV2 (4). From the top panel one can see that the object suffers from multiple close encounters with every of the three terrestrial planets, in particular with the Earth. This series of close encounters ends with an impact to Sun, after a dramatical increase of eccentricity

Family/group	Time [Myr]	a [AU]	e	i [deg]	Tisserand Par.	Variation in %
2002 RN137 (clone)						
Hungaria	0	1.8552	0.1175	22.82	1.51625	0.0
First enc. Mars	0.050	1.8551	0.1625	25.46	1.48297	2.2
leaves Hungarias	0.063	1.8540	0.1904	23.47	1.49585	1.4
NEA - Amor	64.016	1.7817	0.2719	29.09	1.40315	7.5
NEA - Apollo	72.670	1.8166	0.4478	28.23	1.33699	11.9
2000 SV2						
Hungaria	0	1.8517	0.1850	24.97	1.48231	0.0
leaves Hungarias	0.004	1.8517	0.1988	24.16	1.48684	0.3
NEA - Amor	0.085	1.8490	0.2991	24.29	1.45306	2.0
First enc. Mars	0.226	1.8501	0.2331	23.25	1.48553	0.2
First enc. Earth	77.926	2.0553	0.5048	3.98	1.47785	0.3
First enc. Venus	78.544	2.1634	0.7259	5.61	1.23792	16.5
NEA - Apollo	77.889	2.0485	0.5036	0.73	1.48050	0.1
Sun-impact	85.545	2.3541	0.9999	20.89	0.23267	84.3

Table 7 Dynamical evolution for clones (2002 RN137 and 2000 SV2) describing to which asteroid group the objects belong to; in addition the semimajor axes a , the eccentricity e , the inclination and the Tisserand parameter are given in columns 3 to 6.

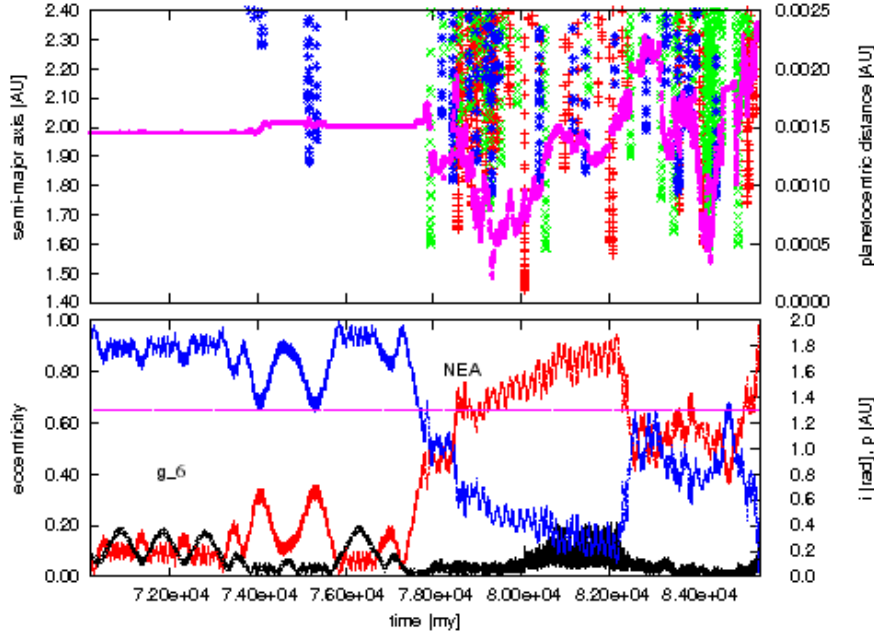


Fig. 4 Dynamical evolution of a clone of 2000 SV2 becoming a Sun-grazer. Upper panel: semimajor axes (left, continuous horizontal line) and planetocentric distances to the terrestrial planet (vertical lines: crosses for Venus, exes for Earth, asterisks for Mars); lower panel: eccentricity (darker line) and inclination. Asteroids is in g_6 till after a deep close encounter with the Earth it becomes a NEA. For more see text.

and inclination (lower panel), thus switching to a retrograde orbit (maximum inclination to $\sim 60^\circ$.) after 85.405 Myrs.

3.3 Analysis of close encounter data

As example of the dynamical evolution we show in detail two examples out of our sample, where one (2002 RN137) ends as member of the Apollo group, and the other one (2000 SV2) has an impact on the Sun. Both show the characteristic behaviour of changing the group membership inside the NEAs, In Tab. 7 details on the escape times from the Hungaria region are given. Here “escapes” mean that the Hungarias’ orbital elements (a, e, i) fall outside the range of semi-major axes a , eccentricity e , or inclination i defined in a former section¹¹. The fugitives leave the group very soon, sometimes in less than 10^5 years, apart from 2000 WM124, that has only 5 clones which escape after CE to Mars. If the escapers have CE with Mars, they become NEAs (table ??, note that here the ones that becomes soon NEAs have an higher probability than the others to become sun grazers, see 4), in particular Apollos and Amors, but changing family during the last millions of years of the integration. Freistetter (2009) showed, that asteroids frequently change the NEA family due to their chaotic orbits, and that a “fuzzy” characterisation is sometimes more adequate to retrieve quantitative results than a strict classification. When belonging to the Amor group within 11 Myr (average on the whole) or less they become Apollos, and in many cases also Atens and Atiras, e.g. 1997 UL20, whose clones have a huge number of close encounters with all the terrestrial planets. Their eccentricities will increase after close encounters with Mars, and then impacts on all terrestrial planets are possible, even on the Sun. and giving the corresponding orbital elements. Last column is the variation in percentage with the first value: it is clear that till the asteroid is not a NEA, the Tisserand parameter ($T_{ast} = \frac{1}{2a} + \sqrt{a(1-e^2)}\cos(i)$, with a =semimajor axis of the asteroid, e =eccentricity of the asteroid and i =inclinaition of the asteroid.) is almost constant and close to the average value for the Hungaria family, that is 1.54646 ± 0.01681 (to compare for the Vesta family it is 1.73977 ± 0.00580 (Galiazzo 2012)).

From the close encounters we derive important information about the duration, the angle of deflection, the velocity and we found interesting correlations.

We study the relation between the duration¹² and the absolute number of close encounters, with one or more terrestrial planets. The mean duration of close encounters depends on how many planets the Hungaria can approach, the more planet it reaches the shorter the encounters. In fact for those objects that have the lowest probability to have close encounters we find a high duration, i.e. the maximum value for Mars is for 2000 WM124 (0.65 d), that also has only a small probability to have a close approach to the latter, and does not approach the other two planets.

Of course the singular event depends mainly on the entry velocity¹³. On average the mean duration of close encounters with Mars is about half a day, and this is the highest value for the terrestrial planets. In summary: 0.27 ± 0.05 d for Venus, 0.36 ± 0.09 d for Earth and 0.55 ± 0.05 d for Mars.

The Hungarias seem to have more close encounters¹⁴ with the Earth in quantity respect to

¹¹ $1.78 < a[\text{AU}] < 2.03$, $12^\circ < i < 31^\circ$ and $e < 0.19$ in orbital element space

¹² Inside a sphere of radius equal to 0.0025 AU around each planet.

¹³ The “entry velocity” is the velocity of the asteroid when it arrives for the first time at the maximum distance established for a close encounter from the planet

¹⁴ relatively to each own orbit.

the other planets (Mars: 57 ± 44 , Earth: 77 ± 53 and Venus: 42 ± 33), even if almost all of them has a close encounter with Mars, but not with the other two terrestrial planets (see table 2).

The average dispersion angle Θ ¹⁵ is very small, though in some cases we get values of more than 60° of deflection and even more than 90° like asteroid 1991 JM. It reaches very high angle of deflection because of entering deeply the Hill's sphere many times. When the asteroids approach very close to the planet (see, i.e., table 8, the closest point to the relative planet for the maximum angle of deflection is always smaller than the average one.) but with low relative velocity, this is very clear in fig.5 where we see clearly the connection between speed of the asteroid, its angle of deflection and perigeum to its relative planets. There are usually very large deflections for speed with $v \lesssim 10 \text{ km/s}$ and the contrary with $v \lesssim 60 \text{ km/s}$. Θ_{Mars} ¹⁶ is smaller than the mean value of Earth and Venus has the smallest respectively: $0.43^\circ \pm 0.15^\circ$, $0.83^\circ \pm 0.76^\circ$ and $0.41^\circ \pm 0.16^\circ$ (see table 8 from some relative cases).

The minima of the relative distance to the planet are related to the cases with maximum deflection¹⁷, compare table 8 for the average minimal distance versus the minimal distance at maximum deflection. The average entry velocities for the fugitives are 27.80 ± 1.71 , 21.54 ± 2.30 ¹⁸ and $10.85 \pm 1.01 \text{ km/s}$ respectively for Venus, Earth, and Mars.

There seem to exist a strong concerning the inclination and entry velocity: we find that whenever there is a close encounter with a terrestrial planet – apart from when there is an impact (see section 3.3) – every time the inclination increases, the same holds for the velocity of the asteroids and vice versa (see fig. 7). Only when there is an impact, as in fig. 7, the behaviour is the opposite and with a high peak. Also the eccentricity increase, like the adimensional encounter-velocity, but this one, just before the impact get in a chaotic behaviour.

Other interesting correlation exists between the angle of deflection and minimal distance to the planets (see fig. 8): In the space $\Theta - v$ the data fits well with the equation

$$y = 2 * \left[\frac{\pi}{2} - \arctan(ax^b) \right] \quad (1)$$

(where $y = \Theta$ and $x = \Delta_{\min}$ (perigeum), which is very similar to the approximation of the system to a 2BP (two body problem, planet and asteroid), where the angle of deflection is

$$\Theta = 2 \arcsin \left(1 + \frac{\Delta_{\min}^2 v^4}{G^2 (M + m_0)} \right)^{-1/2} = 2 \arccot \left(\frac{Gb}{Mv^2} \right) \quad (2)$$

(v = encounter velocity, G = gravitational constant, M = mass of the planet, m_0 = mass of asteroid, in our case, negligible), see Greenberg (1981) . b is the impact parameter, coming from the equation:

$$1 - \left(\frac{b}{\Delta_{\min}} \right) - 2 \frac{G}{Mv^2 \Delta_{\min}} = 0 \quad (3)$$

¹⁵ It was previously defined in section 2. We may also use the term “angle of dispersion”.

¹⁶ If we don't consider angle $> 2.5^\circ$, the large majority of close encounters has deflections smaller than this value, see the average for the maximum angle of deflection per clone in table 8.

¹⁷ Except few cases with very high deflections, due to possible biases in computations, when there is not enough data available to compute the angle of deflection accurately.

¹⁸ This would give a larger impact velocities in case of an impacts than the average one found for all type of impactors, so it seems that Hungarias' impactors are faster than the average.

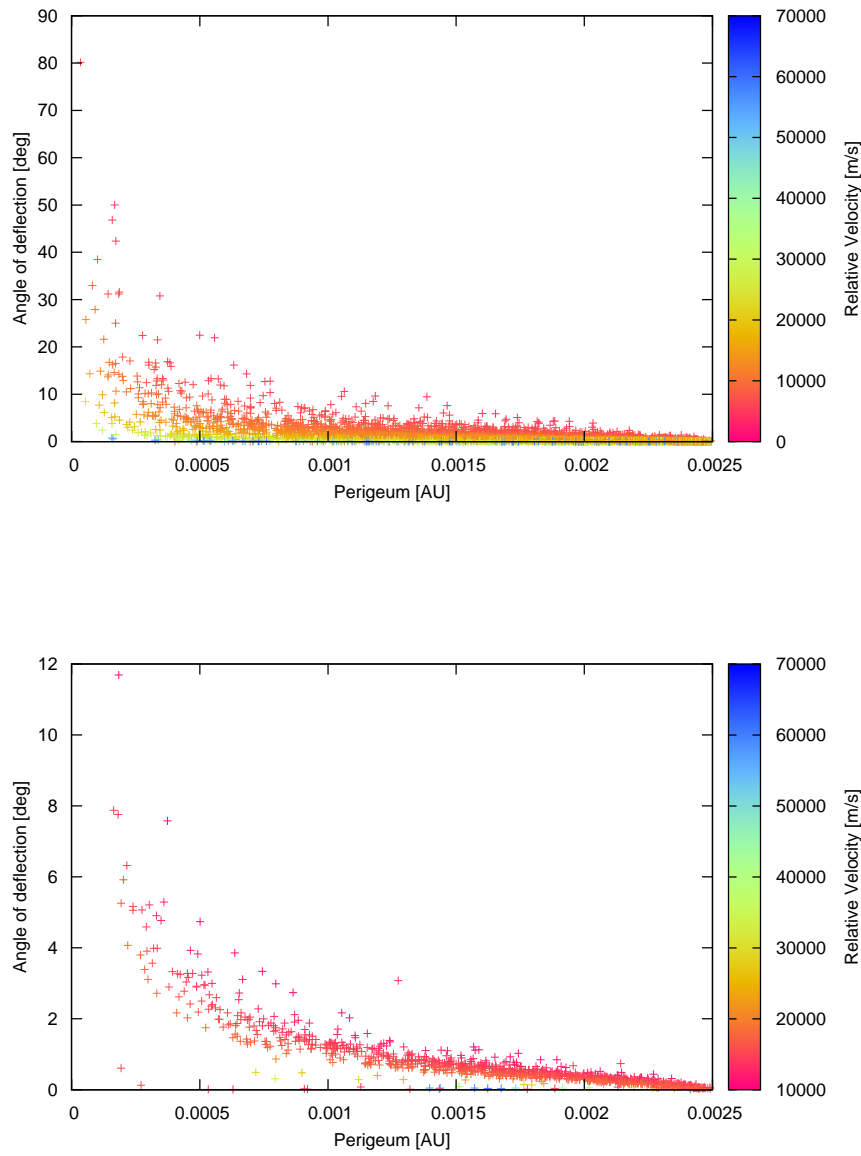


Fig. 5 Relation in close encounters of 1997 UL20 (left panel) 1996 VG9(right panel) and its clones with Earth between relative velocity of the asteroid in front of the planet, perigees and angles of deflection. Here it is very visible the large deflections of 1997 UL20 (where we have also a deflection of 80° in front of the ones with minor deflections).

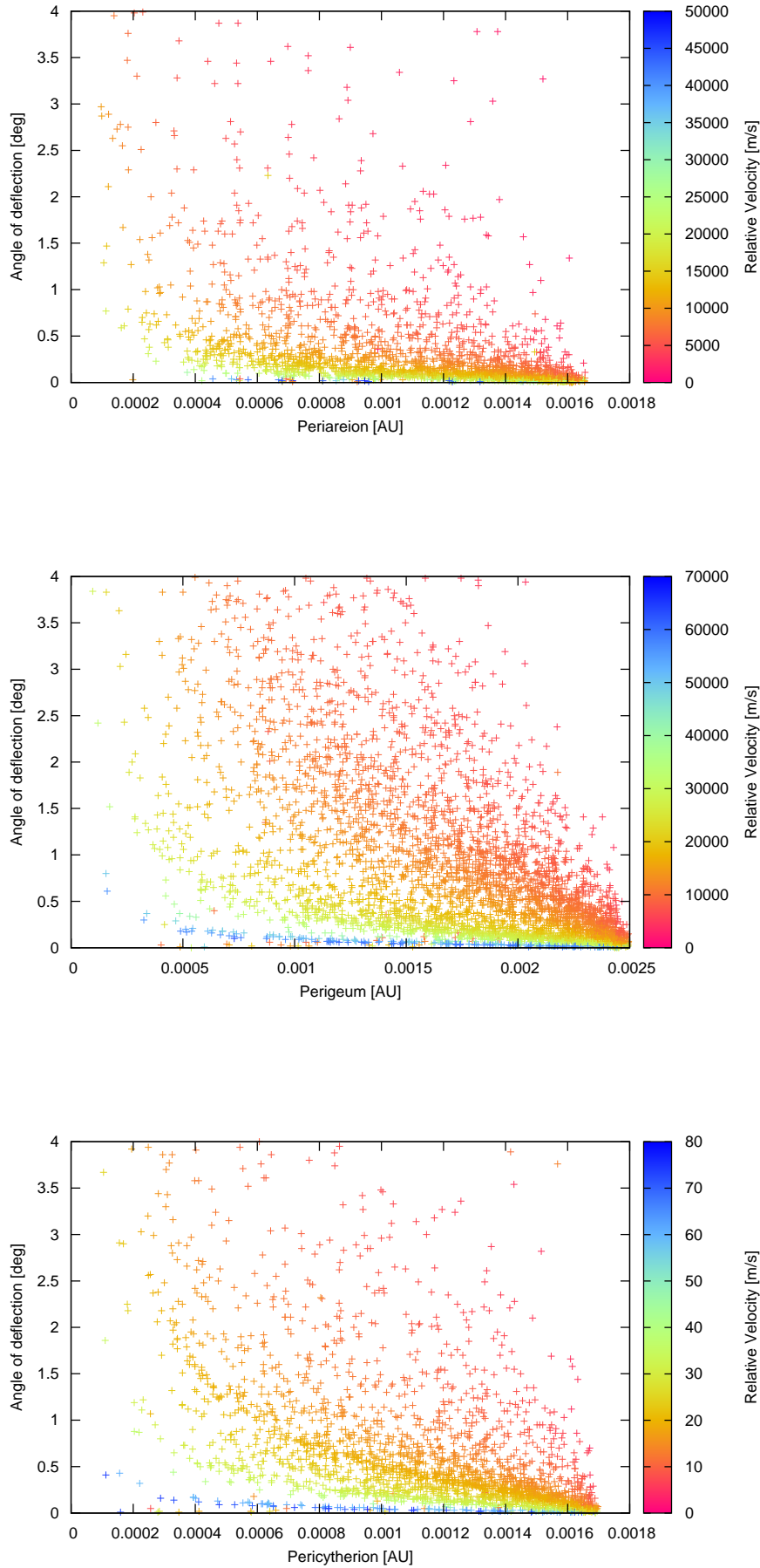


Fig. 6 Relation in close encounters of 1997 UL20 (left panel) and its clones with Mars, Earth and Venus (from up to down) between relative velocity of the asteroid in front of the planet, perigees and angles of

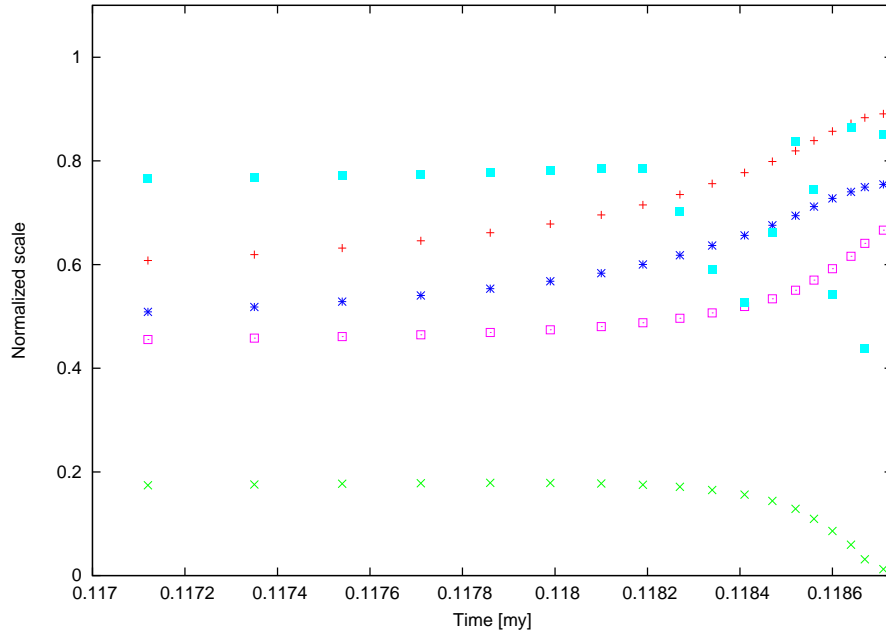


Fig. 7 Impact moment: the cross indicates the velocity (AU/day); the fullisk, the adimensional encounter-velocity (see Braggar and Wiegert); the asterisk is the eccentricity; the empty square shows the semimajor-axis (AU/2) and the exe, the inclination (Degrees/100). The time is from 97732.75611107 My (from the beginning of the integration).

For the case of Earth encounters for the fitting function for 1997 UL20, $a = 1.556 \cdot (10^5)$ and $b = 1.81$, and for 1996 VG9, $a = 64.773 \cdot (10^5)$ and $b = 2.22$ (fig.8), this shows again that the angle of deflections are higher for 1997 UL20; instead the mean values for the all fugitives are $a = 21.152 \cdot (10^5)$ and $b = 1.943$, values that stand between the previous two described fugitives. The fits for Mars are usually more accurate, because there are more close encounters (more data); the best fits have errors $\lesssim 2\%$ the measure, and usually they are not more than $\sim 14\%$.

The fitting functions have different parameters for each individual asteroid, because the asteroids enter in different ways statistically we have different average values. The behaviour of this fitting depends strongly on the entry trajectory into the “Moon-Earth zone”, it depends on the closest distance to the relative planet and the entry velocity in particular. The fitting parameters are better constrained for asteroids which enter inside the “Moon-Earth zone” with a velocity less than the relative escape velocity. So we can predict the pericenter distance from the angle of dispersion (or vice versa) for asteroids with velocity mentioned just before, seeking the fitting function as a function of two parameters. This function can be approximated very well by the equation on the angle of deflection coming from the 2BP. There is a relation also for Δv (difference between entry-velocity and exit-velocity) and the deflection angle – the higher the angle of deflection is, the bigger is the difference in the velocity.

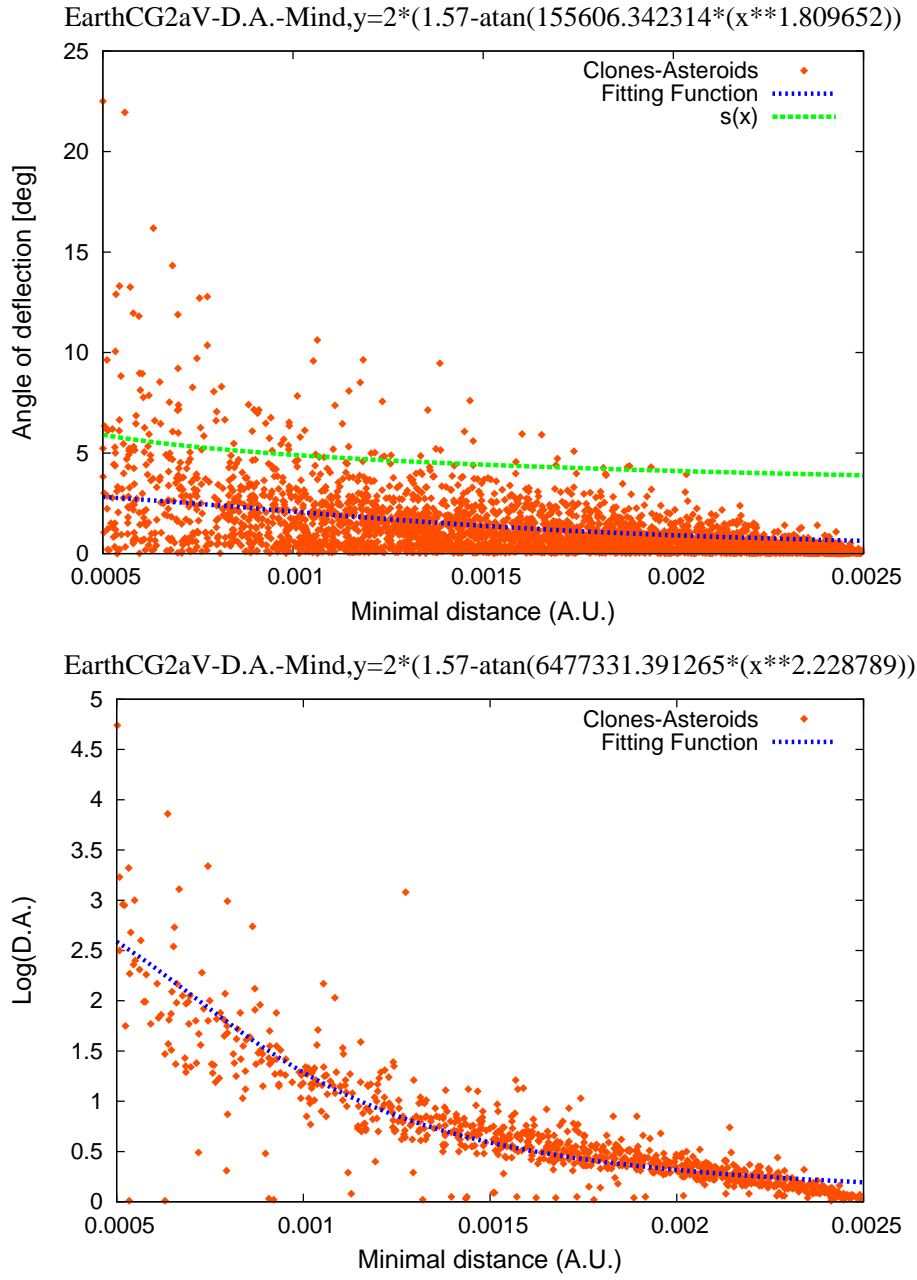


Fig. 8 Correlation in a close encounter with the Earth by all the clones of asteroid 1997 UL20 (top panel) and of 1996 VG9 (bottom panel) between angle of dispersion and perigee with two fitting functions: (a) eq. 1 and (b) $y = dx^e + f$ (with free parameters d, e, f , where b is always negative). The first equation is the best one in fitting the data.

Planet	Asteroid	$\langle\Theta\rangle$ [deg]	$\langle p\rangle$ ($\times 10^{-4}$) [AU]	$\langle\Theta_{\max}\rangle$ [deg]	Θ_{\max} [deg]	$p(\Theta_{\max})$ ($\times 10^{-4}$) [AU]
Venus	2002 RN137	0.38 ± 0.24	4.442	1.58 ± 1.26	3.84	1.768
	Davasobel	0.34 ± 0.25	5.540	1.43 ± 1.70	6.78	2.774
	1992 QA	0.42 ± 0.38	5.375	2.29 ± 2.15	6.39	4.616
Earth	2002 RN137	1.03 ± 0.91	4.127	8.56 ± 10.93	44.06	1.1158
	Davasobel	0.80 ± 0.69	6.430	2.91 ± 2.76	9.20	3.070
	1992 QA	0.85 ± 0.84	6.046	5.33 ± 5.46	16.41	2.709
Mars	2002 RN137	0.33 ± 0.14	2.058	3.17 ± 3.33	16.56	1.245
	Davasobel	0.22 ± 0.10	2.2484	1.48 ± 1.22	6.18	1.006
	1992 QA	0.32 ± 0.13	2.234	2.86 ± 4.23	21.98	1.665

Table 8 Data of the planetary close encounters for some fugitives. $\langle\Theta\rangle$ = mean angle of deflection averaged over all clones and for the real asteroid, $\langle\Theta_{\max}\rangle$ = mean of the maximum angles of deflection per planet per clone, Θ_{\max} = absolute maximum angle of deflection, $p(\Theta_{\max})$ = pericenter distance (in units of 10^{-4} AU) of the close encounter at the maximum angle of deflection, $\langle p\rangle$ = mean pericenter distance averaged over all clones and for the real asteroid.

Planet	Asteroid	\bar{v}_{ent}	$\bar{v}_{ent,max}$	$\bar{v}_{ent,min}$
Venus	2002 RN137	27.32 ± 7.42	35.10	19.26
	Davasobel	29.76 ± 7.38	37.42	24.38
	1992 QA	29.28 ± 11.67	42.03	22.66
Earth	2002 RN137	20.03 ± 6.64	29.94	12.60
	Davasobel	20.36 ± 6.07	28.64	16.54
	1992 QA	22.32 ± 12.17	31.32	13.05
Mars	2002 RN137	10.71 ± 1.71	16.63	5.96
	Davasobel	13.15 ± 1.72	19.12	7.91
	1992 QA	11.05 ± 1.50	16.29	7.14

Table 9 Data of the planetary close encounters for some of the 11 Hungarias which deflect more than 0.08 AU in semimajor axis from their original orbit. All the velocities was measured at the distance for an encounter relative to the planet: \bar{v}_{ent} = mean entry velocity, $\bar{v}_{ent,max}$ = mean maximum entry velocity, $\bar{v}_{ent,min}$ = mean minimum entry velocity. We found that exit velocity is always equal the entry velocity inside a range of 0.01 km/s.

Our study of putative impacts on the terrestrial planets also concerns the possible diameter of the craters caused by Hungaria asteroids. In order to estimate what effects an impact of a Hungaria asteroid has, we need to know their impact velocity (and kinetic energy) and the impact angle. The estimates of the Hungaria-impactors are based on the assumption that the impactor has a spherical shape and is a non-binary system¹⁹.

It is important to notice that by frequent close encounters the asteroid's inclination decreases to values close to those of the planet's orbits; usually the closer the body gets to the

¹⁹ many asteroids (and comets) have irregular shapes, which can affect impact energy calculations; approximately 16% of NEAs larger than 200 m are binary systems (Margot et al. 2002).

Planet	Asteroid	\bar{i}_{ent}	$\bar{i}_{ent,max}$	$\bar{i}_{ent,min}$	\bar{i}_{exit}	$\bar{i}_{exit,max}$	$\bar{i}_{exit,min}$
Venus	2002 RN137	25.80 ± 14.42	36.30	15.31	25.82 ± 14.38	36.30	15.35
	Davasobel	26.16 ± 14.43	39.43	16.68	26.15 ± 14.41	39.47	16.67
	1992 QA	23.94 ± 20.60	33.47	17.88	23.91 ± 20.62	33.28	17.88
Earth	2002 RN137	22.72 ± 12.55	36.29	11.13	22.66 ± 12.62	36.32	11.05
	Davasobel	25.61 ± 11.23	36.85	18.92	25.51 ± 11.26	36.69	18.91
	1992 QA	27.34 ± 22.88	39.25	15.72	27.39 ± 22.96	39.20	15.77
Mars	2002 RN137	23.26 ± 4.14	33.76	12.44	23.26 ± 4.14	37.72	12.43
	Davasobel	27.00 ± 4.67	38.59	15.66	27.00 ± 4.68	38.59	15.66
	1992 QA	23.85 ± 3.40	32.15	16.01	23.85 ± 3.40	32.15	16.02

Table 10 Data of the planetary close encounters for some of the 11 Hungarias which deflect more than 0.08 AU in semimajor axis from their original orbit. All the inclinations was measured at the distance for an encounter relative to the planet: \bar{i}_{ent} = mean entry inclination, $\bar{i}_{ent,max}$ = mean maximum entry inclination, $\bar{i}_{ent,min}$ = mean minimum entry inclination, \bar{i}_{exit} = mean exit inclination, $\bar{i}_{exit,max}$ = mean maximum exit inclination, $\bar{i}_{exit,min}$ = mean minimum exit inclination. Observing the average inclination, everytime, apart one case, the inclination decreases after the encounter.

planet, the more it will be influenced, and thus the impact probability! The known impact structures on Earth range from small circular bowls only a few hundred metres in diameter to large complex structures more than 200 km in diameter (French 1998), with ages as old as 2 Gyr. The biggest known craters on Earth are Vredefort and Sudbury craters, see table 13 for details. The “projectiles” capable of forming craters on the terrestrial planets today come primarily from three populations (Ivanov et al. 2002a):

1. asteroids from the main belt
2. Jupiter-family comets from the Kuiper Belt
3. long period comets from the Oort Cloud

Bottke et al. (2002) showed that the asteroids provide most of terrestrial impact craters coming from $a < 7.4$ AU orbits. Some hundreds of NEAs have a diameter ≥ 1 km like the Hungarias. For our fugitives the diameters range from approximately 1 km to ~ 2.5 km, see table 1.

3.4 Craters

During the integrations some clones have an impact with a terrestrial planet. We assume an impact if the body surmounts the limit for the atmospheric entry (see fig. 1 of Westman et al. (2003)), for this cutoff we have chosen a value for the Earth equal to 65.4 km^{20} . For the other planets we derived an empirical equation using a constant k which depends on the scale height h_{atm} of the atmosphere, measured in astronomical units (1 AU = 149597870.7 km) and the (surface) density of each planet (for parameters see table 1):

$$k = \rho^{(E)} h_{tot}^{(E)} / h_{atm}^{(E)}$$

²⁰ see <http://neo.jpl.nasa.gov/news/2008tc3.html>

Planet	radius R [km] pressure P [bar]	density ρ_1 [kg/m^3] h_{atm} [km]	density ρ_2 [kg/m^3] g [m/s]
Venus	6051.8	2800	3000
	92	15.9	8.9
Earth	6371.0	2500	2750
	1.01325	8.5	9.8
Mars	3396.2	2500	—
	0.00636	11.11	3.71

Table 11 ρ_1^{Earth} and ρ_2^{Earth} are the densities of sedimentary and crystalline rock, respectively, (Collins et al. 2005); ρ_1^{Venus} is the (surface) density given by the fact sheet of NASA (<http://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html>) and ρ_2^{Venus} is the upper limit of basalt given in http://geology.about.com/cs/rock_types/a/aarockspecgrav.htm. ρ_1^{Mars} is the density for Mars; we have considered the lower value for andesite (see the link mentioned just before). For the scale heights of the atmospheres (h_{atm}) we have chosen for the Earth the value mentioned at <http://neo.jpl.nasa.gov/news/948tc3.html>. All the other parameters come from the NASA fact-sheets for each planet.

where

$$h_{tot}^{(E)} = r^{(E)} + h_{atm}^{(E)}.$$

Here $h_{atm}^{(E)}$ is the scale height of the Earth atmosphere, $\rho^{(E)}$ the density, and $r^{(E)}$ is the radius of the Earth (also in astronomical units). The atmospheric entry (r_{imp}) for Venus and Mars is given by the equation:

$$r_{imp} = r^{(P)} + h_{tot}^{(P)} \rho^{(P)} / k.$$

We estimate the diameter of the objects (table ??) from the absolute visual magnitude H_v and visual albedo p_v by the formula (Fowler & Chillemi 1992)

$$D = \frac{1329}{\sqrt{p_v}} 10^{-H/5}$$

which gives quite precise results with an error of less than 10% – if the diameter is 220 km the error is about 20 km, see Galiazzo (2008). The computed diameters of the Hungaria impactors fit to those of real observed Hungarias, as is visible from table 1.

From our integrations we find a lot of impacts with Venus (see tables 12 and 14), but the impact probability (computed like in Dvorak & Freistetter (2001)) for this planet is the lowest. Only if we consider the impact probability together with the number of impacts in the numerical integration (table 12), we find that Venus is the planet with more impacts by Hungaria fugitives, in our case especially for 1997 UL20 (7.19×10^{-8}). That object has the highest number of close encounters with Venus, due to the fact that its initial conditions are just in the M3:2 MMR, which immediately increases its eccentricity. The probabilities computed from the results of our integrations confirm the trend and the values found in Ivanov et al. (2002a) for bodies with $H < 17$ mag, even if the value for Mars is very small compared to our results (0.21 compared to 0.34). This bias is due to the fact that we use a small sample and have restricted ourselves to a special group of asteroids. Averaging on the fugitives which have impacts (9 out of 11), we find an average probability that ranges from $(2.20 - 3.49) \times 10^{-8}/yr$, this means that a fugitive should orbit between 0.026 – 0.045 Gyr²¹ at its currently observed orbit before impacting one of the terrestrial planets.

²¹ 0.040 Gyr for the Earth, meaning that impacts by Hungarias may happen since $\sim (0.46 - 0.92)$ Gyr ago (see also section 1). However this is only one of the probable suggestions, so caution may be advised before completely accepting these connections.

The impact angle is defined via the angle of the planetocentric velocity vector with the normal to the target's surface:

$$\cos(\theta_{norm}) = \frac{\mathbf{v} \cdot \mathbf{n}}{\|\mathbf{v}\| \cdot \|\mathbf{n}\|}$$

and so $\theta = 90^\circ - \theta_{norm}$. We compute the diameter of the crater by means of the equations for the transient crater diameter (Collins et al. 2005):

$$D_{tc} = 1.161 \left(\frac{\rho_i}{\rho_t} \right)^{1/3} D_i^{0.78} v_i^{0.44} g^{-0.22} (\sin \theta)^{1/3},$$

here D_i is the diameter of the impactor, ρ_i its density (for the Hungarias we chose $\rho_i = 1700 \text{ kg/m}^3$, McEachern et al. (2010)), and ρ_t is the density of the target. For the final crater diameter (McKinnon & Schenk 1985) it follows:

$$D_c = 1.17 \frac{D_{tc}^{1.13}}{D_*^{0.13}},$$

with D_* the transition diameter inversely proportional to the surface gravity of the target (Melosh 1989), with the nominal value for the Moon of $D_{*,Moon} = 18 \text{ km}$ (Minton & Malhotra 2010):

$$D_* = 1.62 D_{*,Moon} / g^{(P)}.$$

Earth: Grieve & Shoemaker (1994) suggest that it is possible to distinguish two populations of craters: (i) craters with diameters between 24 to 39 km, the oldest being 115 Myr; and (ii) craters with diameters from 55 to 100 km, the oldest being 370 Myr. Ivanov et al. (2002a) assume that craters smaller than $\sim 20 \text{ km}$ belong to the younger set, so Hungarias should have formed craters younger than 115 Myr. This should be compared to the diameters found from our computations (see table 13,14 and 15), with the biggest crater formed by 2002 SV2 (20.89 km).

Mars: In the equatorial geologic-geomorphic units of Mars (latitude $\leq 35^\circ$), there are craters that range from 4 to 10 km (Condit 1978), these could be created by Hungarias, like the putative crater made by a clone of 1996 VG9.

Venus: If we take a look at the Venus database²², we find also here a lot of craters which would fit with the putative ones created by Hungarias.

Concerning the impact energy, we compute it based on the equation given by Collins et al. (2005):

$$E = \frac{\pi}{12} \rho_{ast} D_{ast}^3 v_i^2$$

This is the energy equivalent in megatons (Mt) if we consider the impactor's diameter D_{ast} expressed in meters, its velocity v_i in km/s and the density ρ_i in g/cm^3 . As can be seen the energy depends strongly on the diameter of the impactor and on the impact velocity, which is computed by the equation given in Collins et al. (2005):

$$v_i = v_\infty \frac{\rho_i D_i}{\rho_i D_i + \frac{3P_{pl}}{2g_{pl} \sin \theta}}.$$

(using v_∞ as the speed of the asteroid before the atmospheric entry, D_i impactor diameter, P_{pl} atmospheric pressure). The maximum impact energy released for the Earth is $\approx 4.18 \times$

²² <http://www.lpi.usra.edu/resources/vc/vcnames/>

Planet	$P (\times 10^{-8})$ Asteroid and P (10^{-8})	$I (\times 10^{-2})$ Asteroid and P (10^{-8})	IC_F Asteroid and P (10^{-8})
Venus	2.20 1997 UL20 7.19	2.59 2000 SV2 6.32	9.80 2001 XB48 2.72
Earth	2.47 1997 UL20 6.96	0.93 2000 SV2 4.83	6.87 2001 XB48 2.78
Mars	3.49 2002 DN3 8.34	0.34 1992 QA 5.70	9.01 2002 RN137 5.40

Table 12 Average impact probability per Gyr P (10^{-9}) for the 100 Myr integration, number of impacts I = number of clones with an impact divided by the total number of clones for every fugitive, given for each planet and additionally for the asteroids with the highest probability of impact. $IC_F = (P \times 10^{10}) (I + 10/N_t)$ is what we call the “impact computational factor”, $N_t = 540$ (one asteroid was integrated with 40 clones) is the total number of bodies in all the integrations. Venus has the highest probability to have impacts among the terrestrial planets.

10^5 Mt, more than forty thousand times the energy released to create the Meteor Crater in Arizona, USA (Shoemaker 1983). For that case the impact velocity is very high, and for the Earth we do not have strong deceleration by the atmosphere like it happens for Venus, where due to high friction caused by the dense atmosphere there are lower impact energies. In fact, impacts with the highest energies happen more frequently on the Earth than on Venus and Mars (see table 13, 14 and 15). The impact energies for Venus are on average lower than on Mars.

Table 13, 14 and 15 summarize the data for the impacting asteroids, including the energy released by the “crash” of the impactor and the diameter of the crater²³ on the two main types of surfaces of the Earth (sedimentary rocks and crystalline rocks); two different surfaces for Venus (strong andesite and strong basalt), and one for Mars (andesite). For each planet they are shown the maximum & minimum crater diameter, the diameter similar to a real crater and average values per planet (in between the parenthesis the total number of impacts per planet). D_1 and D_2 are the crater diameters for a sedimentary surface (the bigger one) and for crystalline surface, for the Earth; strong andesite surface (the bigger diameter) and strong basaltic surface for Venus, and only feeble andesite surface for Mars. θ is the angle of impact; E , the energy released by the impact and $E_{Nord.Cr.}$ displays how many times we have the energy of the Nördlingen crater (the energy released by the impactor in the Ries Crater is ~ 15 megatons, see the impact database of the Planetary Space Science Centre), a thousand times the energy released at Hiroshima (15 kilotons, see <http://www.world-nuclear.org/info/inf52.html>) compared to the energy released by the Hungaria escapers. Then v_∞ is the velocity at the atmospheric entry, v_{imp} , the impact velocity and v_e is the relative escape velocity of the planet. There are also the orbital elements (a , e , i) at the border distance to be considered as a close encounter; the time of the impact t from the beginning of the integration and the disclosure time to arrive from the lunar distance to the target (to the limit of the atmospheric entry), Δt .

In the case of 1997 UL20, there are the maximum number of impacts, 11 different ones. Dellen fits well with the time range of impacts (its impact event is considered to have happened ~ 89 Myr ago, <http://www.passc.net/EarthImpactDatabase/Europe.html>), considering

²³ All the diameters refer to an asteroid that does not suffer from fragmentation during its flight through the atmosphere.

Asteroid Energy [Mt $\times 10^5$] semi-major axis [AU]	D_1 [km] $E_{Nord.Cr.}$ eccentricity	D_2 [km] v_{∞} [km/s] inclination [deg]	θ v_{imp} [km/s] time [Myr]	v_e [km/s] Δt [h]
Earth craters				
1999 UF5	9.21	8.92	47	
0.205	0.76	13.47	14.20	11.2
2.1568	0.5426	1.93	37.622	11.37
Davasobel	27.47	26.61	55	
4.181	15.48	15.23	16.05	11.20
0.8020	0.3918	6.10	89.182	9.5
2000 SV2	20.00	19.37	38	
5.881	21.78	22.03	21.89	11.20
1.9904	0.6810	4.82	16.578	6.54
Average(5) ¹	20.77	20.12	58	
3.467	12.84		25.34	11.20
1.4158	0.5790	7.5101		
Vredefort crater	140.00 ²	—	—	—
855.821 ²	570.55	20.00 ⁴	—	11.2
Dellen	19.00	—	—	—
1.034 ³ 5	3.83	20.00	—	11.2

Table 13 Earth-impacts

its diameter (Ivanov et al. (2002a)). Also the Ries crater fits into the range, but it is speculated that it originated by a V-type asteroid, not belonging to the Hungarias, because the impactor seems to be consistent with achondrite.

The inclination at the atmospheric entry looks very high for Mars and contrary for Earth, while the eccentricities continue to increase going interiorly the solar system. The average impact angle seems higher for the Earth and also the biggest craters appear here.

Venus craters				
2002 DN3	5.82	5.16	17	
0.074	0.275	43.43	9.79	10.2
1.4287	0.8840	34.78	73.713	2.52
2000 SV2	19.60	19.15	43	
4.851	17.965	31.21	19.88	10.2
0.9269	0.3755	46.47	97.403	3.87
1997 UL20	10.50	10.26	37	
0.426	1.579	21.86	11.01	10.2
1.1297	0.5478	3.59	13.948	5.68
Average(11) ¹	11.41	11.25	39	
1.020	3.777		13.02	11.20
1.2172	0.5992	20.1758		
Virginia	18.1 ⁶	—	—	—
Outi	10.3 ⁷	—	—	—

Table 14 Venus-impacts.

Mars craters				
1996 VG9	6.50		3	
0.614	2.275	9.26	9.32	5
1.8688	0.1896	21.76	40.317	13.08
1991 JM	13.25		50	
0.155	0.574	13.01	13.25	5
1.8766	0.2248	25.21	70.191	8.75
2000 SV2	22.85		53	
2.689	9.958	14.57	14.80	5
1.9777	0.2183	34.31	90.380	9.04
Average(4) ¹	15.19		39	
1.347	4.988		15.20	11.20
1.7866	0.3681	33.4039		
Dromore	14.8 ⁸	—	—	—
Endeavour	22.0 ⁹	—	—	—

Table 15 Mars-impacts.¹ Total number of impact for all the clones for each relative planet.² Melosh (1989)³ We used the density of 4 Vesta to compute it: 3.67 g/cm⁴.⁵ and diameter of the asteroids equal to 10 km (Turtle & Pierazzo (1998))⁶ we compute it using a density of 2.6 g/cm³ (for dellonite Walker et al. (1976)), an average velocity of 19.3 km/s (Ivanov et al. 2002a), and a putative diameter for the asteroid of 2 km.⁷ www.lpi.usra.edu/resources/vc/vchome.html⁸ like Virginia⁷ <http://planetarynames.wr.usgs.gov>⁹ <http://marsrovers.jpl.nasa.gov/newsroom/pressreleases/20080922a.html>

GROUP NEOs	a (AU) a	e e	i (deg) i	H_{vrange} (mag)	ρ_{range}	Types
<i>A</i>	1.246 ± 0.050	0.840 ± 0.150	9.4 ± 8.0	11.8-18.5	0.3-0.5	Xe,S,C
1620 Geographos	1.245	0.336♣	13.34	0.33	S	
<i>B</i>	2.157 ± 0.05	0.543 ± 0.150	1.9 ± 8.0	11.8-18.5	0.3-0.5	Xe,S,C
2201 Oliato	2.173	0.712♣	2.52	15.2	0.43	Sq
5751 Zao	2.102	0.424	16.07♣	14.8	0.36	X
<i>C</i>	1.990 ± 0.050	0.681 ± 0.150	4.82 ± 8.0	11.8-18.5	0.3-0.5	Xe,S,C
3551 Verenia	2.093	0.487♣	9.51	16.8	0.37	v♣
<i>D</i>	0.7367-0.9957	0.334-0.571	2.33-16.53	11.8-18.5	0.3-0.5	Xe,S,C
5604 (1992 FE)	0.927	0.405	4.79	16.4	0.48	v♣

Table 16 Elements of earth-colliding Hungarias at 0.0025AU and NEOs from http://ssd.jpl.nasa.gov/sbdb_query.cgi#x. The most probable Hungaria' origin NEO in this table is 5751 Zao (1992 AC), an Amor asteroid of 2.3km (Delbó et al. 2003), in the range of Hungarias' diameter. ♣ means "value out of the range", because in some cases one value is not inside the range.

Looking in detail at the impact velocity our results range from 14.2 to 30.18 km/s for the Earth. These values are larger than the results given by Ivanov & Hartmann (2002b); Chyba (1993) ($\langle v \rangle = 19.3$ km/s for an asteroid with $H_v < 17$ mag and $\langle v \rangle = 18.6$ km/s for $H_v < 15$ mag), even if that sample is for asteroids with $D < 50$ m. Hungarias seem to arrive faster on the average than other types of asteroids having close encounters with the Earth. Concerning Mars the range of velocities is from 9.32 to 23.42 km/s with the maximum value higher than for the average asteroids found in Ivanov & Hartmann (2002b), so the Hungarias come faster to Mars, too. On the other hand we find lower velocities for Venusian impactors, our results range from 5.24 to 24.57 km/s, against the average velocity of 24.2 km/s of Ivanov & Hartmann (2002b). Speaking about the Earth, its atmosphere protects us from most NEOs smaller than a modest office building (40 m diameter, or impact energy of about 3 megatons). From this size up to about 1 km diameter, an impacting NEO can do tremendous damage on a local scale. Above an energy close to a million megatons (diameter about 2 km, like our Hungarias), an impact will produce severe environmental damage on a global scale. The probable consequence would be an "impact winter" with worldwide loss of crops and subsequent starvation and disease. Still larger impacts, can cause mass extinctions, like the one that ended the age of the dinosaurs 65 million years ago (15 km diameter and about 100 million megatons²⁴). Such sizes are hardly encountered among the Hungarias.

We found some NEOs (in the JPL Small-Body Database Search Engine) that fits well with the elements of our impactors, also inside the ranges of the albedos and absolute magnitudes of the Hungarias, also spectra types gave a good fitting, when they are present. Concerning the 6 impacts found on the Earth we figure out 4 groups of elements that range inside the "impact-zone" (elements of the orbit at 0.0025 AU before the impact, the most consistent group is the third one in the table, see table 16, the border are given with a reasonable specific range²⁵).

We have as a result of our integration the majority of the Hungaria escapers become NEAs and some finish their lives as Sun-grazers, if they do not collide with a planet before

²⁴ http://impact.arc.nasa.gov/intro_faq.cfm

²⁵ For the most consistent group (*D*): $x_{\text{max}_{\text{max}_{\text{element}}}} = x_{\text{max}_{\text{element}}} + \Delta_x$ and $x_{\text{min}_{\text{min}_{\text{element}}}} = x_{\text{min}_{\text{element}}} + \Delta_x$ where $\Delta_x = (x_{\text{max}_{\text{element}}} - x_{\text{min}_{\text{element}}})/2$, i.e. $a_{\text{max}} = 0.9309$, $a_{\text{min}} = 0.8014$, so $a_{\text{max}_{\text{max}}} = 0.9957$ AU and $a_{\text{min}_{\text{min}}} = 0.7367$ AU

that. There is a small number of them (with a low probability) that leave the inner main belt crossing the region of the Centaurs and Trans Neptunian Objects (TNOs). Perhaps we could find some Hungarias in the outer solar system, probably as comets, because we observe very high eccentricities when they are NEAs and even high inclinations (more than the initial conditions). In the case of Hungaria-derived Apollos or Amors, the Earth is flattening the orbits of the asteroids (decreases the inclination) close to the ecliptic.

In fact we see that these asteroids tend to decrease their heliocentric distance, apart some cases that get into a hyperbolic orbit (this happens in close encounters with Mars after they begin to be Mars-crossers), and some have impacts with the Sun (after $t > 90$ Myr of integration).

We think that the former collision started from a period in which massive bodies (with diameters bigger than at least 30 km) collided in the Main Belt region, presumably all started with an initial collision in the inner main belt region for a body with probably high inclination ($i \geq 23^\circ$), the half value of the interval in inclination of the Hungaria group, see section 2 and another object with less or equal to the minimum inclination of the group today ($i \leq 16^\circ$). This collision may have given birth to the E-belt (Bottke et al. 2011) and this last one gave origin to the present Hungarias and a great part of the NEAs. We underline that the majority of the Hungaria escapers change their membership when they are NEAs, as it has been discussed in detail in Milani et al. (1989), Dvorak & Pilat-Lohinger (1999), and Dvorak & Freistetter (2001). The semi-major axes continue to decrease, contrary to the eccentricity that is continuously increasing with increasing number of close encounters, especially with Mars (many times just before being a NEA) and by passing through MMRs with different planets and some secular resonances. Also the inclination increases until the body becomes a NEA, but after it decreases by some degrees.

It is visible that whenever there is a close encounter with Mars there is a jump in semi-major axis and this push to Mars is given mostly by MMRs²⁶ by effective resonances in this specific zones:

$$\begin{aligned} 1.780 < a < 1.800 \text{ AU: } E5:12, V11:43, V8:31 \\ 1.890 < a < 1.935 \text{ AU: } J22:5, M7:10, M5:7, M18:25 \text{ and } V4:17 \\ a > 1.935 \text{ AU: } M2:3 \end{aligned}$$

and some minor 3BMMRs (Jupiter–Saturn–asteroid) such as $7 : -5 : -1$ or $13 : -8 : -2$ with the combination of secular resonances at high inclinations.

MMRs with Mars play a very important role for Hungarias, and in combination with MMRs with Jupiter, Earth and Venus push the fugitives toward Earth, Venus and even Sun. We also note in particular that the average perihelion for 100 Myr of the escapers is 0.939 AU quite close to the Earth perihelion.

The fugitives are planet crossing asteroids (PCAs) at least in 91% of the cases in 100 Myr, their angles of deflection can be very high – up to more than 90° sometimes, even if on average it is less than 3° (the biggest one is for Venus, *sim2.46*). The duration of their close encounters is maximal for Mars, ~ 0.5 days, and minimal for Venus, ~ 0.25 days, somewhere in between for the Earth ($\sim 1/3$ days). We could define a relation $2 : 3 : 4$ (Venus:Earth:Mars) for the durations of close encounters with terrestrial planets, this is because the encounter velocities of the asteroids are very high at Venus and lower at Mars.

The Hungaria's encounter velocities seem to be faster than the average values for the all the real asteroids that come close to the terrestrial planets and so they do look like to cause craters bigger than the average ones similar to their asteroid-diameter.

²⁶ where the eccentricity is very excited

The resulting craters range roughly from 10 to 30 km of diameter, the impacts might produce severe environmental damage on global scale, but not extinction. The planet with the highest probability of impact is Venus and the impacts with the Earth seem to happen on a very short time-scale compared to other MBAs. We underline that some NEOs fits with Earth-colliding Hungarias-NEAS found by this work, i.e. Amor asteroid 5751 Zao.

We will continue with this work to make comparisons of dynamical behaviour with the introduction of non-gravitational forces (like the Yarkovsky effect) and also with other main-belt families (a study on the Vesta family is in preparation) and the Moon too, considering studying for their impacts and statistical analyses on their crater dimensions, angle and velocities of impacts, and energy releases.

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